

Interrelating Binarity, Physical Properties and Orbital Evolution of Near Earth Asteroids: A New Numerical Approach

Mihailo Čubrović

*Department of Astronomy – Petnica Science Center, P. O. B. 6, 14104, Valjevo,
Serbia and Montenegro*

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Send proofs to: Mihailo Čubrović

E-mail: cygnus@EUnet.yu

Abstract

Possible connections between the physical properties of Near-Earth Asteroids (NEA) and their orbital evolution were explored, with emphasis on binary asteroids. Our main starting hypothesis, suggested from the observations, was that the NEA population contains considerably higher percent of binaries compared to the Main Belt. The simulation covered simultaneously both orbital evolution and evolution of physical properties, which is the main improvement in comparison to the previous researches of this kind. Physical evolution due to tidal forces and collision/disruption events was described with TREESPH hydrocode. The results show typical evolution paths of some types of NEA: asteroids with a satellite, synchronized binaries, single fast rotators, double asteroids. The two latter types and their physical properties match closely to some observed NEA, while the two former ones have not been detected in observational practice. We conjecture that this is partly due to selection effects of current observational techniques but partly also because some of them are likely to evolve into different types of objects (e. g. single slow rotators) through the processes we have not taken into account in our simulation. The total percentage of binaries among NEA can be estimated to 12%. We have to notice, however, that more detailed simulations, performed for longer time spans, are needed to confirm our results.

Key words: asteroids, composition; asteroids, rotation; collisional physics; satellites, general

1 Introduction

The population of Near-Earth Asteroids (NEA) is generally considered to be an especially interesting group of asteroids, in part because of their complicated origin, and in part because of their accessibility to observations. Physical properties and physical evolution of these objects are relatively poorly known¹. The basic concept of most models is the rubble-pile structure: an aggregate of loosely (exclusively gravitationally) bonded blocks. Observational evidences for the rubble-pile structure (as well as for other possible aggregate structures) can be found e. g. in [Richardson et al. (2002)]. The algorithm for simulations of this kind can be based either on an N-body code [Leinhardt et al. (2000), Richardson et al. (1998), Solem & Hills (1996)] or on a hydrocode [Love & Ahrens (1996a), Richardson (2001), Richardson & Bottke (1996)]. Some recent papers take into consideration both gravity and cohesive forces [Michel et al. (2002)]. The initial conditions of events like collision or close approach to the Earth are usually estimated from coarse (and occasionally quite non-physical) empirical distributions. Therefore, despite some progress in understanding tidal and collisional processes among the NEA, we still lack a consistent model of their physical evolution and formation of binary systems. The laboratory experiments of collisional processes can also yield some information but their validity is questioned by the problems of scaling.

On the other hand, the orbital evolution of NEA is known in much more detail. A particular form of chaos is especially notable in this population: although it

¹ Under “physical properties” we assume any properties which are not orbital elements and are not directly dependent upon the orbital motion, e. g. shape, binarity, rotation state, internal structure, existence of precession, etc.

is strongly affected by numerous close approaches, the whole population seems to remain in an approximately steady state. Despite the lack of long-scale predictability for particular objects, some detailed models of NEA population have been published [Rabinowitz (1997), Morbidelli et al. (2002)]. According to the mentioned papers, the 3 : 1 and ν_6 resonances seem to be the most important source of NEA although the Mars crosser (MC) population also has some importance.

In this paper, we give some results of our numerical simulation of orbital and physical evolution of NEA, with special emphasis on the formation and properties of binary systems. The main contribution of this paper is the simultaneous treatment of orbital motion and collision/disruption events, which is, as far as we know, carried out for the first time. One of the primary objectives of this research is the explanation of observational evidences that the NEA population has substantially larger percent of binary asteroids than the Main Belt [Margot et al. (2002)]. Tidal deformations (and disruptions) during close approaches, collisions among the NEA, as well as mutual tidal influences in binary systems, cause very complicated perturbations of both orbital elements and physical properties. Many of the mentioned processes are probably interrelated. Therefore, we expect this simultaneous treatment to resolve some previously unknown mechanisms and to explain evolution paths of some typical NEA objects. Some of our findings are not entirely new but at least yield a direct confirmation of earlier proposed scenarios, while others contrast to the usual understanding of binaries formation.

Of course, the most significant drawback of this approach is the large amount of calculations that have to be done since many processes are being simulated at the same time. This limits the number of objects involved as well as the

interval of the simulation. An important factor is also the limited resolution of the hydrocode. In addition, some of the initial conditions are not known very well, which also affects the validity of the results. Therefore, this research should only be considered as a qualitative picture of some processes among the NEA, given on a fictitious representative ensemble of objects – it is not a model of NEA population nor does it give valid predictions for the evolution of any particular object.

The second section gives a short review of the methodology, including the orbital integrator, the treatment of non-gravitational influences, the dynamical model of binary systems and the hydrodynamical model adopted for the description of physical evolution. The third section describes the implementation of the simulation and the simulated system. Results are given in the fourth section. Some theoretical implications of the results, as well as some comparisons to the previous research are discussed in the fifth section. The sixth section sums up the conclusions.

2 Methodology

2.1 Orbital integrator

Basic request for the orbital integrator was efficiency rather than precision. As it is mentioned in the first section, we were seeking only for a qualitative description of the orbital movement, not for the exact orbital elements. We adopted a second-order symplectic integrator, proposed by [Wisdom & Holman (1991)], usually known as the “Mixed-Variable Symplectic” integrator (MVS). Its efficiency is usually considerably higher than that of ordinary integrators (e. g.

Bulirsch-Stoer), while the precision remains valid for many purposes, despite the (typically) low order of MVS integrators.

In our integrator, we used a second-order algorithm. The integration included four planets (Earth, Mars, Jupiter, and Saturn). The Mercury’s mass was added to that of the Sun, while the Moon’s mass was added to the Earth’s mass. Asteroids were included as test particles.

Our integration scheme is, however, somewhat different from the original concept of [Wisdom & Holman (1991)], since it includes some improvements, proposed by [Saha & Tremaine (1992), Saha & Tremaine (1994)]. This version of the MVS integrator gives the error of the order $\mathcal{O}(\varepsilon^2\tau^2)$, where ε denotes the planets to Sun mass ratio, and τ stands for the average time step.

The non-gravitational forces (the Poynting-Robertson drag and the Yarkovsky force) could not be included directly since they make it impossible to write the equations of motion in Hamiltonian form needed for our integrator. As it is well known, these effects are largely negligible for objects that exceed about 100 m. However, some recent results [Vokrouhlický (1999), and references therein] show that the Yarkovsky effect could significantly influence evolution of some objects by putting them into mean motion resonances. Therefore, we decided to include this effect by applying periodical corrections to the semimajor axes of the asteroids’ orbits, using the linear approximation derived by [Vokrouhlický (1999)]. His equations do not separate the seasonal part (dependent on the orbital period) and the diurnal part (dependent on the rotation period) of the effect but treat them together. We omit them here for the sake of conciseness; they are very complicated and can be found in the aforementioned reference. It is enough to mention that the only parameters

that correspond to particular asteroid are density, mean radius, thermal capacity, and thermal conductivity. The former two characterized each asteroid in the simulation (for details see the third section) while the latter two were fixed, calculated from the parameters of the equation of state (see the third subsection of this section).

2.2 *Dynamical model of binary systems*

As it is well known, binary systems undergo mutual tidal perturbations, which affect their motion around the mutual center of mass. Close approaches to the Earth are also expected to change their dynamical nature. A simple dynamical model was used to describe these events, based on some analytical and semi-analytical results.

Dynamic state of each binary system was characterized by spin vectors, eccentricity and semimajor axes of the components (the latter two, together with the masses, determine the orbital frequency around the center of mass)². The tidal influence was calculated as a series of periodical changes in orbital frequency, eccentricity, and rotational periods, using the analytical expressions of classical tide theory [Peale (1999)]. Since these expressions are complicated and can be found in many classical references, we shall, as for the Yarkovsky drift, omit them.

The close approaches were treated in a semi-analytical way, following the

² We mention here only those parameters which are included in the dynamical model of binary systems; others are mentioned in the next subsection, and all the parameters are listed in the third section.

idea of [Farinella & Chauvineau (1993)]. The relative changes of energy and angular momentum of the system can be expressed as:

$$\frac{\Delta E}{E} = \frac{G^2 m_A m_P}{V b^2} (-2E)^{-\frac{3}{2}} I \quad (1)$$

$$\frac{\Delta L}{L} = \frac{1}{2} \frac{\Delta E}{E} \quad (2)$$

where m_P and m_A denote masses of the planet (in this case Earth) and the asteroid (the whole binary system), while V and b represent the velocity of the planet in the reference frame of the asteroid and the impact parameter, respectively. The dependence of the perturbation upon the geometry of the approach (parameterized with three angles, see [Farinella & Chauvineau (1993)] for details) is contained in the non-dimensional integral I . Analytical solution of this integral does not exist in the general case. [Farinella & Chauvineau (1993)] approximate it with a Gaussian random variable, starting from the rectilinear approximation. We, however, calculated (numerically) and tabulated the value of I for different geometries of the encounter, which allowed us to adopt a more realistic, hyperbolic approximation. During the simulation, the actual value for each close approach was calculated as a linear interpolation from the table with respect to the independent parameters, which allowed better efficiency than immediate integration.

2.3 *The hydrodynamical model of asteroids*

The core of our hydrodynamical model is the hydrocode usually known as TREESPH, given by [Hernquist & Katz (1989)]. It is a combination of the Smoothed Particle Hydrodynamics code (SPH), and the Hierarchical Tree Method (HTM), an algorithm developed for hierarchical work with clusters

of objects. The latter gives to TREESPH also some good features of N body algorithms. All the details of our model and its specific properties are not of interest here and will be published elsewhere. In this subsection, we shall mention only some basic ideas and differences from the published models.

First, we shall briefly revisit the SPH formalism. This method was given by Gingold and Monaghan (1977; according to [Hernquist & Katz (1989)]) and it has become widely accepted for applications that require high efficiency and modest precision. It is a Lagrangian particle code, which is mathematically based on integral interpolation. The interactions among the particles are described via an interpolation function. Value of a physical field $f(\vec{r})$ in a given location (i. e. for a given particle) is calculated as:

$$f_{SPH}(\vec{r}) = \int W(\vec{r} - \vec{r}'; h(\vec{r}, \vec{r}')) f(\vec{r}') d\vec{r}' \quad (3)$$

where W denotes the kernel, and the integration is performed over the whole volume of the system (in this case asteroid). The h parameter is the smoothing length, which roughly corresponds to the resolution of the hydrocode. The kernel characterizes the strength of the interaction, so it typically drops very quickly when $r - r'$ becomes large. Its integral is normalized to unity. As it can be seen from (3), the smoothing length is spatially variable, and it changes both locally and globally. This spatially adaptive smoothing length is a peculiarity of TREESPH; the original SPH uses constant smoothing length. In practice, of course, the integration turns into summation over a set of discrete particles. For the kernel, we adopted the cubic spline proposed by Monaghan and Lattanzio and given by [Hernquist & Katz (1989)]. Its value drops to zero for $r - r' > 2h$. The evolution of the system is described, as usually, by continuity equation, momentum equation, energy equation and equation of

state (EOS). The procedure for discretization of these equations can be found in the aforementioned reference and will be omitted here. The well-known fourth-order adaptive step Runge-Kutta algorithm [Press et al. (1997)] was used for the integration.

For the EOS we adopted the Tillotson equations [Benz & Asphaug (1999)]. Since they are somewhat less known, we will describe them here. The basic idea is to consider analytically only two extreme cases (concerning the energy of the system); otherwise, the resulting EOS is calculated via linear interpolation. If the volume density of energy is less than the energy of incipient vaporization ($E < E_{iv}$) the pressure is given by:

$$P = \left[a + \frac{b}{1 + \frac{E}{E_0 \eta^2}} \right] \rho E + A\mu + B\mu^2 \quad (4)$$

If the volume density of energy grows larger than the energy of complete vaporization ($E > E_{cv}$) the previous equation becomes:

$$P = a\rho E + \left[\frac{b\rho E}{1 + \frac{E}{E_0 \eta^2}} + A\mu \exp\left(\beta - \beta \frac{\rho_0}{\rho}\right) \right] \exp\left[-\alpha \left(\frac{\rho}{\rho_0} - 1\right)^2\right] \quad (5)$$

The parameters A , B , a , b , α , β , E_0 , E_{iv} , E_{cv} , ρ_0 , μ are dependent on the material. Following [Love & Ahrens (1996a)], we adopted their values for basalt taken from [Benz & Asphaug (1999)]. Density of each particle was also taken to be equal to the density of basalt ($\rho = 2.7 \text{ g cm}^{-3}$). Initially, the particles were distributed in a face-centered cubic array, which gives the average density about 1.8 g cm^{-3} (less than the theoretical value because of finite dimensions of asteroids).

The role of HTM is to make the calculations of interactions among the particles more efficient. Summation of interactions between each two particles in general

case requires an $\mathcal{O}(N^2)$ algorithm. In HTM, particles are formally arranged in clusters, which may replace single particles in hydrodynamical calculations. During the force evaluation, the algorithm creates a tree with clusters (which have the physical meaning of three-dimensional cells in space) at the nodes. Therefore, distant particles contribute to the resulting force only as clusters while near ones contribute to it directly. Of course, some empirical criterion for clustering has to be adopted; we have used a polynomial law derived from numerical experiments. The whole procedure (tree construction and the force evaluation) is now performed in $\mathcal{O}(N \log N)$ time, and it makes the model plausible also for the ballistic phase of an impact (unlike the traditional SPH code).

As it has already become clear, the model asteroid is simply a set of gravitationally interacting particles in an external gravitational field (originated from some other body, see next section for details). We completely neglect material strength, so this is a purely “rubble-pile” model. Friction and fractures are also neglected. Particles are represented as non-elastic spheres of finite radius. The reference frame is always the center of mass of the system. We used this model to simulate collisions and tidal disruptions.

Criterion for escaping particles was one of the most problematic issues since the safest solution – direct integration long enough for all the escaping particles to actually escape – was not possible due to computational reasons. Speed criterions are not plausible because of the non-sphericity of the asteroid. We implemented a criterion suggested by W. F. Bottke (e-mail communication): simply to look for the particles with the absolute value of potential energy larger than the kinetic energy. Although somewhat dangerous because of artificial energy oscillations, which are sometimes produced by SPH, this criterion

generally seemed realistic. The second major issue was the detection of satellites that may form during a collision/disruption event. Since the satellites of asteroids are among the main objectives of our research this criterion had to be imposed more exactly, also because we had to calculate its starting orbital elements (to be used by the dynamical model, see the previous subsection). We decided to use the semianalytical results based on Hill’s equations [Hasegawa & Nakazawa (1990)], which allowed us to calculate the orbital elements and mark the fragment as a satellite if its orbit turns out to be stable (i. e. orbit which does not include the collision with the main body; hyperbolic orbits are eliminated by the previous test, since they are equivalent to the escape). Finally, the simulation of a particular event was considered complete when all the non-escaping particles either fall back to the asteroid, or start moving on elliptical orbits as satellites.

3 Model and simulation

The simulated system was designed as a representative ensemble of objects that are in source regions for NEA population and therefore can be expected to become NEA relatively quickly. Since we supposed that most of the interesting events (e. g. collisions) happen during the transit to the NEA region, we decided to start with objects in the source regions, and not with objects which have already become NEA. We also decided to work with fictitious objects, since any selection of known objects could result in a biased ensemble and, on the other side, as we have already mentioned, the precision of the simulation does not give valid predictions for any particular object. Therefore, our simulation was intended to follow the migration processes in general and to allow

the analysis of typical NEA after they pass through the transition mechanisms and, possibly, collision/disruption events.

The simulated system contained 160 objects – one sixth of the estimated current NEA population [Morbidelli et al. (2002)]. The interval of the simulation was 10 Myr. The initial orbital elements were calculated from distributions given in the aforementioned reference. The mentioned paper considers the following source regions: the 3 : 1 resonance, the ν_6 resonance, the MC population, the comets of Jupiter family (JFC), and the outer belt (OB). We omitted the last two sources (from which come 14% of NEA, according to [Morbidelli et al. (2002)]) since their transition mechanisms tend to be very complicated and beyond the scope of our research. Relative populations of 3 : 1, ν_6 and MC regions were, respectively 44%, 29%, and 27% (the mentioned 14% of JFC and OB were proportionally distributed among the first three regions). For exact distributions of orbital elements, see [Morbidelli et al. (2002)].

Each object was characterized by orbital elements, mass, spin vector and hydrodynamical model (i. e. coordinates and momenta of each particle, which determine also the density, dimensions and shape). To make the comparison with the observational data easier, we also introduced the mean radius. All the binary systems were marked with a flag since they required two additional parameters – semimajor axis and eccentricity of the orbit around the mutual center of mass. We supposed that the starting population contained no binaries.

The starting distribution of spin vectors (concerning both orientation and intensity) is generally an unexplored subject. Most authors [Chauvineau et al. (1995), Vokrouhlický (1999)] assume an isotropic distribution of spin vectors, so we followed them, largely to

make comparison with [Chauvineau et al. (1995)] easier. Possible problematic consequences of this decision are discussed in the fifth section. For the periods of rotation, we adopted the Maxwellian distribution obtained for Main Belt objects e. g. by [Pravec & Harris (2000)]. Size distribution (distribution of radii) was taken from [Gomes (1997)]; this is an exponential distribution, a widely accepted form for various objects. Finally, the starting shapes were triaxial ellipsoids, with axial ratios distribution taken from observational data given in Uppsala Photometric Catalogue of Asteroids, <http://www.astro.uu.se/classe/projects/apceng.h>

The organizational base of the simulation was the orbit integrator, which was programmed to “turn on” the hydrodynamical simulator if a collision/disruption event is likely to happen. At the end of each time step, a test was performed to check if the asteroid enters the sphere of influence of some other object (an asteroid or a planet). If a direct collision with a planet happened, the asteroid was discarded from the simulation. Otherwise, the hydrocode was activated, which performed the calculations during the collision or close approach (the latter results in deformation and, in the extreme case, disruption). The Yarkovsky drift and, for binaries, the tidal drift were added periodically, as it was described in the previous section. If an asteroid breaks into fragments, at the end of the hydrodynamical simulation each fragment becomes a separate asteroid and continues its evolution separately; its spin vector is calculated from the equation of angular momentum, taking into account also the angular momentum carried by small debris. Bodies with mean radius less than 100 m were discarded since such small bodies require a much more detailed treatment of cohesive forces and non-gravitational influences. Objects that cross the Jupiter’s orbit were also discarded.

The implementation of the simulation cannot treat encounters of three or more

bodies nor can it treat more than one collision/disruption event at the same time step; bearing in mind the probability of these events, we did not take this for a serious disadvantage.

4 Results

4.1 *General remarks*

It is clear that a simulation with so many parameters gives a large amount of numerical results; their detailed analysis is not of interest for this research (although it could be interesting in general). We shall focus only on some characteristic results, which are important for the objective of this paper.

Evolution of the simulated system generally corresponds with current theoretical knowledge about NEA migration and evolution. Processes of transition follow the usual path; the most efficient mechanisms are, as expected, close encounters of the planets, and the most efficient source is, again expected, the 3 : 1 resonance. The MC region was somewhat more efficient than expected. After about 2 Myr the system became relatively stable and the number of bodies in the NEA region became nearly constant. Most of the particles survived until the end of the integration, despite largely chaotic nature of their evolution.

Collisions of asteroids also seem to fit well into current models. The outcome depends on the mass ratio and impact angle, while the relative speed tends to be less important. It seems that the reaccumulation of collisional fragments has a more prominent role than in previous researches [Leinhardt et al. (2000)],

which may be a consequence of partially N-body nature of TREESPH. The bottom size limit for formation of stable rubble-pile objects seems to be about 100 m – 200 m. Of course, these remarks should be treated carefully, as they are only our general notes about the collisions; they are not a result of systematic analysis.

The tidal forces act relatively slowly but in long intervals they can become key factors for an object’s evolution. Low-speed approaches tend to be the most efficient disruption mechanisms while the fast ones usually only slightly deform the asteroid. Still, the outcome largely depends on the initial physical properties of an asteroid. Only in two cases, we detected a complete disruption into many fragments.

Before we start the analysis of the particular types of detected binaries, we shall just briefly comment the spin rate distribution. Among the numbered NEA, this distribution is more or less uniform [Pravec & Harris (2000)] in contrast to the Maxwellian distribution of the Main Belt objects. The natural explanation would be that the NEA do not have the time to achieve a steady, collisionally-relaxed state due to their short lifetime. We conjectured that binary systems are subjected to the more intense evolution (collisional but also tidal) than the rest of NEA population so we expected to find a distribution somewhat more similar to the Maxwellian by taking only the binaries into account. The histogram can be seen in Fig. 1. Strictly speaking, in order to cheque the consistency with the Maxwellian distribution, one would have to normalize the spin rates with respect to the diameter [Pravec & Harris (2000)] but this is not plausible (nor very necessary) for a small set consisting of objects of similar size, as it is the case here. The data for the real objects (for Fig. 1 as well as for the rest of the paper) were taken from Binary

Near-Earth Asteroids page, maintained by Petr Pravec and Peter Scheirich,
<http://www.asu.cas.cz/asteroid/binneas.htm>.

PLACE FIGURE 1 HERE.

The observed objects are all fast rotators, rotating probably on the edge of breakup [Pravec & Harris (2000)]. Our simulation shows the similar peak of the fast rotators but also includes a number of slowly rotating bodies, which makes the distribution visually somewhat more similar to the Maxwellian but still far from it in any quantitative (statistical) sense. Together with the overabundance of the slow rotators among binaries, significant lack of slowly rotating objects is found among the single ones. This problem will be dealt with later; we just remark that it is probably a combination of observational selection effects and various effects not taken into account in this simulation.

4.2 Formation and evolution of particular types of objects

We shall first describe four types of "evolved" objects that could be clearly distinguished at the end of simulation. Their most important characteristics are summed up in Tab. 1. As mentioned, given numerical values should be treated only as rough estimates. Of course, besides these tidally/collisionally evolved objects, there were many "non-evolved" objects – single asteroids with no peculiar features; we focus only on those, which had been subject to intense evolution processes.

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The first type in the table, double asteroids, denotes the binary objects with

non-synchronized rotation (revolution around the mutual center of mass with period different from the rotation period). Under synchronized binaries, we assume the systems that rotate as a rigid body (with a unique spin rate for the whole system); their components are usually very near but they can also be well separated from each other. Because of that, we hesitate to call them contact binaries, although most of them are very close systems (in contact or nearly in contact). To the third type – asteroids with a satellite – belong objects with the mass ratio less than $1/10$, i. e. systems in which one component clearly dominates the other. Under single fast rotators we assume single asteroids with period of rotation shorter than 4 hours. We did not detect single slow rotators, which have been observed [Pravec & Harris (2000)], though we did detect slowly rotating binaries, usually among the contact systems (which have not been observed thus far); we shall consider this problem in more detail later. The double asteroids and the single fast rotators are well known from observational practice [Margot et al. (2002), Pravec & Harris (2000)], so we can say we have reproduced some typical objects. Asteroids with a satellite have not been observed among NEA, nor have been the contact binaries (as we already remarked). Relative abundances of the four types are given in Fig. 2.

PLACE FIGURE 2 HERE.

Double asteroids were detected mostly as outcomes of tidal disruption. Of course, tidal effects influence primarily the Earth crossers; however, these objects occasionally become ejected from the region of the Earth crossers so we could detect them in the whole NEA belt. Mutual tidal perturbations may lead to collision, ejection, or formation of synchronized (usually contact) binaries. However, many systems of this kind were remarkably stable and

were able to survive until the end of the simulation. As we already pointed out, that these systems usually have very fast spin rates (thus accounting for the peak of fast rotators in Fig. 1, which is consistent with the observations [Margot et al. (2002)]).

For the synchronized binaries, we have noticed two formation scenarios. The first one is tidal evolution of the previous type, when the components of a separated binary synchronize and come close to each other. The second scenario is tidal disruption during close encounters. In this case the components may synchronize while staying well separated. Speed of motion during the encounters is typically lower than in the previous case, so the tidal forces become less efficient. Rotation of synchronized binaries is usually slower than for single asteroids, which is expected. This type of asteroids has not been observed, which can be explained with the inability of light curve techniques (upon which results are chosen also the objects for the radar analysis) to detect synchronized systems [Merline et al. (2002)]. It could also happen, however, that contact systems are likely to evolve into some other objects (see the next section).

Asteroids with a satellite seem to be a typical outcome of collisional evolution. According to our simulation, they can be formed only in collisions. Satellite usually forms from ejected material of both components. For colliding objects of similar masses, the most probable outcome is a single fast rotator (the next type) while for larger mass ratios the usual outcome is an asteroid with a satellite. In extreme cases, the only outcome is ejection of many small particles, which do not form a satellite. It is interesting that collisions cannot produce (at least in our simulation) separated binaries which appear as a natural “transient” form between synchronized binaries and asteroids with satellites. However, we have to emphasize the instability of asteroids with satellites. As

it can be seen in Table 1, only three such objects survived for a considerably long time. Satellite usually becomes lost very soon after its formation. This could be one of the reasons that these objects have not been detected: their lifetime is very short. Another important reason is the inability of current observational techniques to detect small satellites [Merline et al. (2002)]: all such objects were detected via either direct flyby of certain Main Belt asteroids.

Single fast rotators were also formed mostly during collisions if the mass ratio of the colliding bodies is of the order of unity. One object of this type was also formed as a consequence of collision of components in a binary system. The latter case, however, seems to be very improbable in practice, as it requires very exact alignment of angular momenta, in order to produce a large enough resulting momentum. During formation of fast rotators, asteroids usually suffer significant mass loss, which is certainly due to many small fragments that become ejected.

The overall percentage of binaries in the ensemble varied about 10%–15%. For the expected mean percentage we obtain 12%, which, according to [Morbidelli et al. (2002)], gives about 110 binaries. This agrees nicely with the analysis of observational data, which gives the percentage of binaries about 16% [Merline et al. (2002), Margot et al. (2002)].

One of the most interesting aspects is, of course, the dynamical evolution of binary systems. Fig. 3 shows the dependence of the final rotational period upon the orbital elements of the binary system – eccentricity and semimajor axis (compare with figures in [Chauvineau et al. (1995)]). The figure has been obtained by interpolating the parameters of objects detected in the simulation. Therefore, it is just a rough visualization of our results. Some parts of the figure (especially those which are near the contact line, see the figure caption

for explanation) are rather uncertain estimates, statistical in nature. Still, we think that the semimajor axis – eccentricity – period dependence is illustrative, both as giving the general picture of the angular momentum distribution and as a kind of confirmation (by the means of "direct simulation") of the Monte Carlo results obtained by [Chauvineau et al. (1995)].

PLACE FIGURE 3 HERE.

The general trend is slowdown of rotation with increase of semimajor axis and eccentricity. A rather strong correlation with the initial conditions can be seen. However, we could not detect any significant influence of the spin vector orientation. This is in clear contradiction with [Chauvineau et al. (1995)] which emphasize strong instabilities of retrograde rotators. A possible cause is that in our, hydrodynamical model asteroids gradually lose most of the rotational energy on internal "heating" (random motion of particles of the asteroid) so the additional tidal action which appears in the case of retrograde rotation does not have sufficient energy to cause the collision of components (which happens in model of [Chauvineau et al. (1995)]). Other aspects of the dynamical evolution of binary systems are qualitatively similar to the results of the mentioned authors: close approaches and tidal forces make asteroids lose energy, which causes either collision or ejection of one component. In the latter case, the larger component loses most of its angular momentum.

Data for the real objects are also shown in the figure. Unfortunately, only seven objects have known (at least tentatively) eccentricities, so this data set is very small. Still, it is encouraging that all the objects except one have the rotational periods which fall into the same color area as the objects in our simulation (because of that we have not colored the observed objects according to their

period – all except one would be of the same color as the background). All of the observed objects are, in our terminology, double asteroids. The single fast rotators have not been quantitatively compared to the observed objects (since there are no other dynamical parameters to compare for single systems but the period of rotation) but their formation is obviously reconstructed in the simulation.

Therefore, we can say we have succeeded to give possible explanations of some typical evolution paths among NEA although we failed to reproduce the single slow rotators. In the following section, we shall try to give theoretical interpretation of these results, and to discuss some other possible consequences.

5 Discussion

Results of our research, although speculative and tentative in nature, do somewhat explain formation of some types of NEA. Our basic concept – simultaneous simulation of both orbital motion and collision/disruption events – seems to have shed some light on the interrelations between these aspects of NEA evolution. Namely, collision and disruption events, which lead to formation of NEA, are strongly associated with transition mechanisms so it seems unnecessary to introduce cosmogonic influences. Of course, disadvantages of this concept are also clear – large amount of calculations, somewhat difficult precise interpretation of results due to many factors and processes involved and uncertain initial conditions for some parameters (e. g. spin vectors, shapes, etc).

Dynamical evolution of binaries shows some similarity with the research of

[Chauvineau et al. (1995)] although, as already mentioned, we have not noticed importance of spin vector orientation. Detailed treatment of internal heating in our model (Tillotson EOS) has probably allowed us to get a more realistic picture of where the energy of tides in retrograde systems goes: it becomes lost in internal “geological activity”.

Continual ejection of small fragments during collisions may be an explanation for the overabundance of small Earth crossers, noticed by some authors [Michel & Froeschlé (2000), Rabinowitz (1997)]. Again, cosmogonic influences seem to be unnecessary if these fragments are taken into account. This could also be a source of some meteor streams (e. g. Geminids). The latter idea is, clearly, only a speculation.

Overall, tidal forces seem to play a more prominent role than collisions. This is in part a consequence of more realistic initial conditions for close approaches but it also seems that our model treats tides better than collisions – the latter require better resolution, taking into account effects of fractures, etc. It seems hard to estimate the consequences of the neglecting of friction. Absence of friction limits the deformation an asteroid can withstand with no disruption and therefore lessens the magnitude of large deformations but, on the other side, it makes small deformations easier. This is qualitatively similar to the conclusions of [Solem & Hills (1996)] and [Love & Ahrens (1996b)].

The most intriguing result is, of course, the lack of single slow rotators and the overabundance of asteroids with a satellite and synchronized binaries. As already mentioned, the reason for the latter lies partly in disadvantages of observational techniques. However, the problem of single slow rotators must be connected with some intrinsic disadvantages of the simulation. The formation of

slowly rotating systems is generally an open problem [Pravec & Harris (2000), Harris (2002)]. Spectrum of possible explanations (concerning our simulation) is very diverse: from inadequate model (equation of state, detection of satellites, etc) to inadequate initial conditions (i. e. some kind of cosmogonic influences) to short interval of simulation. There are some speculations [Brunini (1998)] that various groups of asteroids may have different cosmogonic origin and different early evolution paths. We have also been suggested (Ćirković, personal communication) that slow rotators might be of cometary origin. In that case, their former cometary activity might greatly influence their present dynamical and physical state. Finally, bearing in mind the specific optical properties of some observed slow rotators (e. g. 4179 Toutatis), we think that non-gravitational forces may also have some influence on their spin vectors.

It is, however, more interesting to discuss the possible interrelation between the lack of single slow rotators and the overabundance of synchronized binaries. If the latter is not completely originated in selection effects, it might be possible that some synchronized systems can, over time scales longer than our simulation, loose one of the components and become single slowly rotating asteroids. Unfortunately, this does not seem too realistic the framework of our model since we have not noticed any such phenomenon although the time scale of our simulation is approximately equal to the average lifetime of NEA. Therefore, one has to assume that some more sophisticated processes, first of all the non-gravitational effects (see [Pravec & Harris (2000)] for a discussion of possible influence of Yarkovsky force on the rotation of asteroids; we think similar effects can influence also the revolution of the components around the mutual center of mass) play the key role in such events. So, we can conclude that some of the synchronized binaries we predicted in the simulation do exist

but still escape the observational detection while the rest of them actually dissolve into single fast rotators.

Many questions remain open. A more detailed physical model of asteroids would allow a more refined treatment of collision/disruption events. The primary task would be to include friction and fractures. More realistic treatment of non-gravitational forces (concerning the discussion in the previous paragraph) could also give some new explanations. A better description of chemical and elastic properties of the asteroid material (basalt is only a phenomenological approximation) is also one of possible enhancements for this kind of research.

6 Conclusions

We have carried out a simultaneous numerical simulation of migration and evolution of NEA. This has allowed us to investigate the interrelation of orbital and physical evolution in a more realistic way than in previous, isolated numerical researches. We have confirmed a strong correlation between the formation of binary systems (found to comprise about 12% of NEA population) and events typical for the transition process which makes it unnecessary to introduce cosmogonic influences in order to explain the hypothesis, suggested by the observations, that an overabundance of binaries among NEA exists in comparison to the Main Belt.

We have detected formation of four typical products of tidal and/or collisional evolution: double systems, synchronized systems, asteroids with a satellite and single fast rotators. The simulation gives, in our opinion, sufficiently robust

and realistic models of their formation. Asteroids with a satellite and single fast rotators are formed in collisions, the primary difference being the mass ratio of the colliding bodies: the formation of the latter requires colliding bodies to be of the same order of magnitude, and also some other conditions to be met (e. g. impact angle, spin axis alignment, etc). Asteroids with a satellite, however, seem to be very unstable, for unknown reasons. This instability, together with observational selection effects, can account for the lack of observational evidence of such objects among the NEA.

Double asteroids (well known in observations) are a product of tidal evolution. Synchronized binaries form either from the previous type, or by tidal disruption. We failed to reproduce extremely slow-rotating bodies, which could be due to their peculiar cosmogonic origin or due to the disadvantages of our simulation. We prefer the explanation that a fraction of synchronized systems dissolve due to non-gravitational effects and other sophisticated mechanisms not taken into account in this simulation. The rest of synchronized binaries (those which survive) are likely to be still undetected because of the intrinsic limitations of current light curve inversion techniques.

Generally speaking, tidal forces have proven to be more important than collisions. We noticed the continual formation of small fragments in collision/disruption events, which can explain the overabundance of these objects in the NEA belt and allow a mechanism for keeping their population in a stationary state.

Of course, some results remain unexplained. Fate of synchronized binaries and origin of single slow rotators remain puzzling. Influences of friction and fractures, importance of non-gravitational forces, etc. also require further numerical and theoretical investigations.

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Table 1

Basic properties of typical collisionally and/or tidally evolved objects: physical origin, number of detected objects of that type during the simulation, lifetime (in Myr), periods of rotation and revolution around the center of mass, semimajor axis of the secondary's orbit in units of primary's radii, eccentricity of the secondary's orbit and ratio of the components' radii. Types: 1 — double asteroids, 2 — synchronized binaries, 3 — asteroids with a satellite, 4 — single fast rotators.

Type	Origin	N	T [Myr]	P_0 [h]	P [h]	a [R_p]	e	R_s/R_p
1	tides	18	1.1–4.9	2–11	14–36	2.1–7.1	0.02–0.58	0.11–0.82
2	type 1 and tides	25	1.4–7.3	9–21	$P \equiv P_0$	0.0–7.9	0.02–0.72	0.19–0.89
3	collision	3	0.0–1.2	6–12	17–33	5.3–12.2	0.15–0.48	0.02–0.08
4	collision	9	0.9–3.2	2–4	—	—	—	—

Fig. 1. Spin rate histograms for simulated and observed binaries. While the simulation gives a distribution approaching to the Maxwellian, the observed objects show a remarkable lack of slowly rotating binaries.

Fig. 2. Relative abundances of the four detected types of evolved objects. Only single fast rotators and double asteroids have been observed so far.

Fig. 3. Contour plot of the period of rotation (for binary systems which are not synchronized, period of the larger component is given) upon the initial values of the semimajor axis (in units of the primary's radius R_p) and the eccentricity of the components. The darkest area (in the upper left part) in fact corresponds to the pericentric distances smaller than the primary's radius. Observed binary objects (the seven ones for which an estimate of the eccentricity exists) are also given (marked as stars).

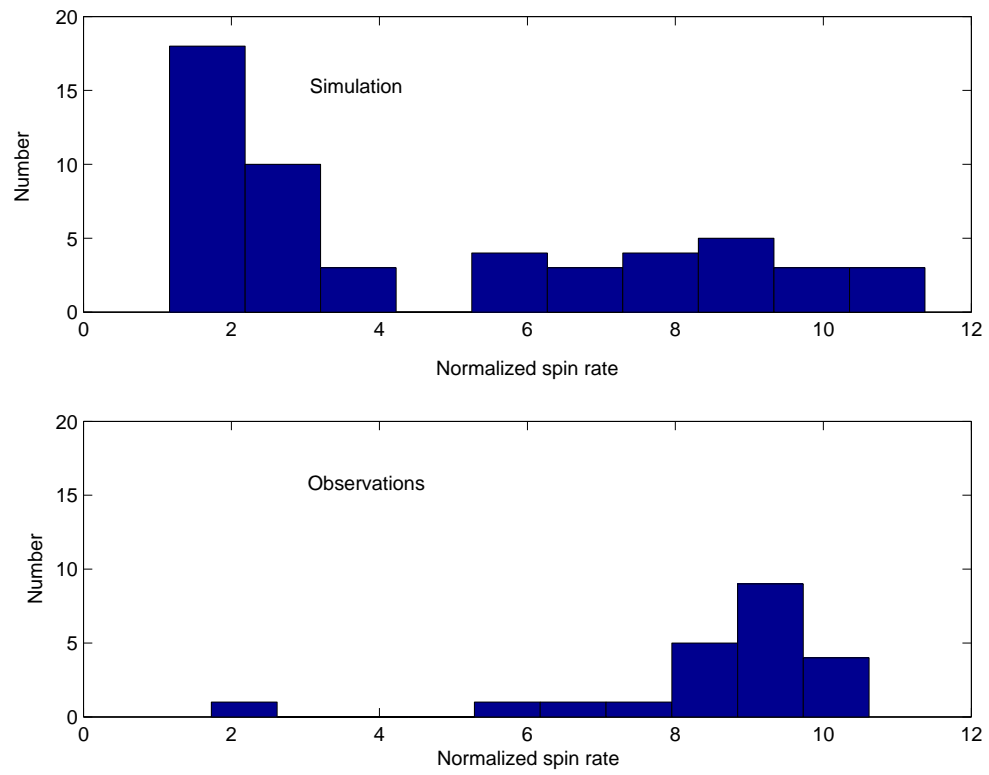


Fig. 1

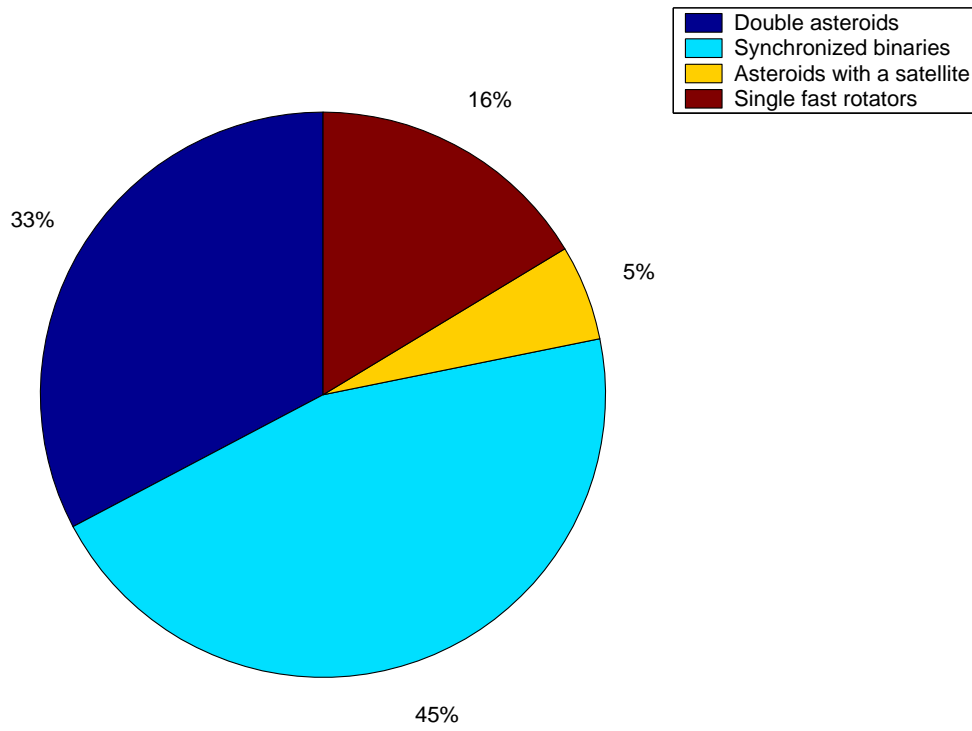


Fig. 2

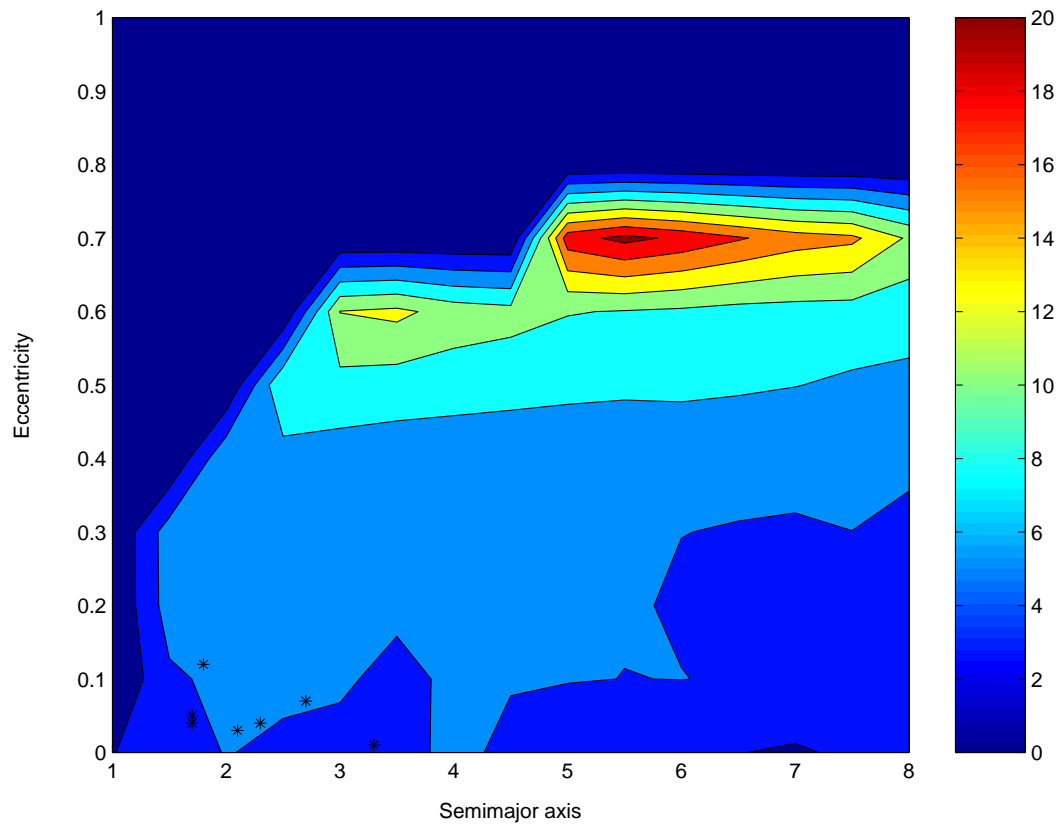


Fig. 3